Introducing a Six-Month Feasibility Study on High Energy Muon Colliders: 23 October, 2000 – 22 April, 2001

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study web page: http://pubweb.bnl.gov/people/bking/mucoll

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Abstract. An open invitation is extended to participate in a six-month study of muon collider technology and physics, running from 23 October, 2000 to 22 April, 2001. An overview is given of the goals and structure of the study, followed by presentation of the working groups' tasks and of straw-man muon collider parameter sets.

I INTRODUCTION

Experiments at high energy colliders continue to be our main experimental tool for advancing our understanding of the elementary particle constituents and fundamental forces of our physical Universe. As one preliminary effort towards the development of future generations of powerful yet cost-efficient colliders, an open invitation is extended to participate in a six-month study of muon collider technology and physics, running from 23 October, 2000 to 22 April, 2001. The study is supported by the Neutrino Factory and Muon Collider Collaboration (1) but welcomes and encourages participation from anyone with an interest in contributing.

II STRUCTURE OF THE STUDY

Lacking the time and resources for hardware development, this study will necessarily concentrate on computer simulations and paper assessments. It comprises a formal backbone of collectively researched tasks along with an open invitation and support base for any and all individual written contributions on topics related to muon colliders.

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The study's tasks are organized under five working groups in the areas of: physics and detectors, cooling, acceleration, the collider ring, and miscellaneous topics. The accelerator-related collective tasks may be summarized as working towards a front-to-back particle tracking simulation of example conceptual designs for muon colliders – essentially "building and testing the muon colliders on a computer".

This high energy muon collider study complements ongoing studies (1) on the sister technology of neutrino factories, which are a non-colliding type of high current muon storage rings. The choice of working groups, etc., emphasizes those areas that are specific to muon colliders and de-emphasizes those where neutrino factories and muon colliders might have rather similar design parameters (e.g. the proton driver and pion production target). This study is also complemented by a much more specialized study (2) that addresses the potential to upgrade from a neutrino factory to a "Higgs factory" muon collider at a lower center-of-mass energy than we consider (see section IV).

The written proceedings from the study will consist of all individual contributed papers, a concise overview write-up and more detailed and specialized write-ups on the subfields associated with each of the 4 topical working groups. These write-ups will reference the individual contributions and, conversely, the purpose of many of the individual contributions will be to provide greater detail on the subtopics summarized in the joint reports. Each participant in the study will receive a copy of the proceedings as a CD and/or bound volumes.

The study's information base and day-to-day operations will be organized around the web page `http://pubweb.bnl.gov/people/bking/mucoll` .

As guidance and encouragement towards individual contributions, the web page attempts to categorize the many diverse areas of muon collider physics and technology where studies would be beneficial. It will continually evolve along with the study, tracking the study's progress by including progressively more specific information on areas for research and on who is doing what. Other information available on the web page includes:

- this document
- straw-man parameter sets for muon collider rings and acceleration scenarios at 400 GeV, 4 TeV and 30 TeV.
- contact information and links
- a table showing significant dates for the study.

The straw-man parameter sets are reproduced in tables 2, 3 and 4, and are discussed further in section IV.

A preliminary table of relevant dates for the study is shown in table 1. Additional dates will be added on the web page during the course of the study, including for working group meetings and or editorial meetings for the proceedings. As can be seen from table 1, it is requested that complete preliminary drafts for all write-ups be made available one month before the end of the study so the content of the individual papers can be meshed with that in the joint reports.

TABLE 1. Significant dates so-far for the study.

Monday, 23 October, 2000	Study commences
Friday, 23 March, 2001	Deadline for first drafts of all papers
Sunday, 22 April, 2001	Deadline for final versions of all papers

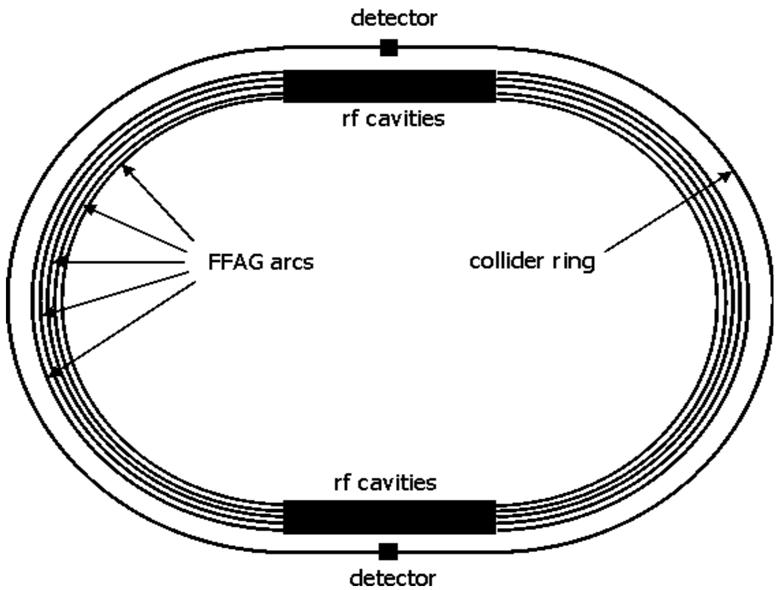

FIGURE 1. Schematic, not-to-scale illustration of the accelerator layout for the final stages of the acceleration scenarios in tables 3 and 4, that bring the beam up to collision energy. A single tunnel contains the collider ring and several rings of FFAG arcs. (The actual number of FFAG rings in the collider tunnel is 3, 6 and 2 for the 400 GeV, 4 TeV and 30 TeV parameter sets, respectively.) All of the FFAG rings share the same rf cavities, shown here in 2 linacs on opposite sides of the tunnel.

III THE WORKING GROUPS

A Physics and Detector Working Group

The more theoretical of two collective tasks for this working group is to categorize the possible scenarios for new physics processes and precision studies at each of the sub-TeV (e.g. 400 GeV), multi-TeV (e.g. 4 TeV) and many-TeV (e.g. 30 TeV) energy scales. The luminosity scales and beam polarizations would be acceptable and/or desirable to probe this physics should be assessed, as should the extent to which our knowledge might develop from intermediate physics studies at the LHC proton collider and/or from a TeV-scale electron-positron collider.

As the more experimental of the two collective tasks, a straw-man detector design should be developed for the 3 straw-man muon collider scenarios. It should be determined whether the different energy scales can be covered by modifying the parameters of one detector design or whether different design strategies would be more appropriate. The event topologies in the detector should be described for each of the given theoretical scenarios. Also, the detector-collider ring interface should be addressed, including design optimization studies on the mask that shields the detector from beam-induced backgrounds. Finally, a tabulation and evaluation of all anticipated background sources for the detector should be presented.

B Cooling Working Group

Muon cooling is the signature technology and dominant technical challenge for muon colliders. No plausible design yet exists for an end-to-end cooling channel that produces the beam parameters required for a muon collider but the first specifications of such channels, with verification using particle tracking codes, might well be achievable within the timespan of this study. Therefore, the collective task of the cooling working group is to develop one or more plausible cooling channel design scenarios for attaining the beam parameters assumed for each of the three straw-man collider scenarios in table 2.

In more detail, the layout and design parameters for the magnets, rf cavities, absorbers and other components throughout the channel should have been evaluated as being technically feasible today or, at a minimum, to represent plausible extrapolations to the time when muon colliders might be built. They should be specified in enough detail that the performance of the entire channel can be verified through Monte Carlo-based track-by-track simulations using one or more of the various codes developed for this purpose. It should also be established that these cooling scenarios are likely to be stable against all known collective beam instabilities.

C Acceleration Working Group

The system for accelerating the muons to collider energies is likely to be the major cost contributor for muon collider complexes, particularly as collision energies rise above the TeV scale. The collective task of the acceleration working group is to develop one or more plausible rf-plus-magnet lattice design scenarios for acceleration to collision energies for each of the three straw-man collider scenarios in table 2, with some effort taken to minimize costs. In practice, this suggests the use of recirculating rings to economize on the amount of rf cavities, minimization of tunnel length by including several recirculating arcs per tunnel and, probably, the use of fixed field alternating gradient magnet lattices (FFAG's) to provide a large enough momentum acceptance for many passes of the beam through the same magnet lattice. The rf and magnet parameters should be reviewed and it should be checked that the wall-plug-to-beam power efficiencies of the scenarios are high enough for the wall-plug power to be within reasonable bounds. It should also be established through particle tracking simulations that the acceleration scenarios are likely to be stable against any collective beam instabilities.

D Collider Ring Working Group

The collective task of the collider ring working group is to develop at least one plausible magnet lattice design for each of the three straw-man collider ring parameter sets in table 2, and to evaluate their performance.

The lattices should include beam scraping, injection and extraction sections and should address the detector interface and the minimization of beam-related backgrounds in the detector (see subsection III A). The assumed magnet parameters should be plausible within today's technology or, at a minimum, represent plausible extrapolations to the time when muon colliders might be built. Particle tracking simulations through the lattices should be performed to evaluate the performance of these lattices vis a vis the dynamic aperture and beam stability. Also, the known classes of potential collective beam instabilities should be tabulated and evaluated for these lattice designs.

E Working Group for Miscellaneous Studies

This working group has two collective tasks. The first concerns those areas where the technology for muon colliders is close to that for neutrino factories, namely, the proton driver, pion production target and target-to-cooling channel. The technology differences between neutrino factories and muon colliders should be summarized for these sub-systems and plausible design scenarios given for muon colliders.

The second collective task is to give a quantitative overview of the global properties and parameters for the study's muon collider scenarios. Component inventories and summaries should be given on the global requirements for cooling and cryogenics, power supplies, switches and pulse forming networks for magnets and rf cavities, etc. Muon survival probabilities should be tracked through the collider complex and a muon budget tabulated. Finally, a first evaluation should be made of overall costs, based both on current costs for components that exist already and on plausible cost goals for the time when the muon colliders could be built. Based on these determinations, a summary should be presented on the anticipated cost-drivers for each of the sub-TeV (e.g. 400 GeV), multi-TeV (e.g. 4 TeV) and many-TeV (e.g. 30 TeV) energy scales.

IV STRAW-MAN MUON COLLIDER PARAMETER SETS

One focal point for the study will be the evaluation of self-consistent straw-man parameter sets for the acceleration and collider rings of muon colliders at center of mass energies of 400 GeV, 4 TeV and 30 TeV. The collider ring parameters are presented in table 2 and the acceleration parameters in tables 3 and 4. The generation of the collider ring parameter sets in table 2 followed a standard procedure that has been described previously (3; 4; 5) and the parameter values iterate on previous parameter sets. The corresponding approximate parameter ranges for the muon collider parameter sets that were discussed in the status report (6) of the Muon Collider Collaboration (MCC) are also included for comparison.

The parameter sets are intended serve as straw-man examples to be criticized, fleshed-out and improved upon by the participants in the study. The physics-related parameters allow evaluations and comments on the physics potential of such muon colliders.

Almost two decades in collision energy are spanned by the parameter sets. The 0.4 TeV parameters are intended to illustrate the lower end of the potential range of muon collider energies. They iterate on previously published parameters at this energy (6), with a higher bunch charge, stronger final focus and higher beam disruption parameter leading to a threefold increase in luminosity. The relatively low beam energy spread and lack of beamstrahlung broadening of the energy spread could allow for physics studies in this energy range that are complementary to those covered by a linear electron-positron collider in this energy range, such as complementary measurements of top pair production near threshold (6).

The 4 TeV collider would be a general purpose discovery machine with an energy reach beyond the LHC for many classes of possible physics processes. The parameter set in table 2 is similar to those considered in previous studies (7; 6) except for a reduction by more than an order of magnitude in the beam current in order to reduce the neutrino radiation (not considered for the parameters in reference (7)) and to also relax the specifications on the proton driver etc.

The high luminosity 30 TeV collider parameter is in the mid-range of the collider energies studied in the HEMC'99 workshop (8). It represents a fairly straightforward interpolation between the 10 TeV and 100 TeV straw-man parameters considered at that workshop and is almost identical to previously published parameters (5).

It is noted that an "s-channel resonance Higgs factory" might emerge as a candidate for a "niche" muon collider at a lower energy than considered in this study in the circumstance that there has been a prior discovery of the hypothesized Higgs particle at a relatively low mass between the current experimental limit of about 110 GeV/c^2 and approximately 150 GeV/c^2. A specific scenario where an assumed existing neutrino factory muon storage ring facility is upgraded to a Higgs factory muon collider is being considered in a more specialized muon collider study (2) that is complementary to this one.

Table 3 gives a straw-man acceleration scenario that reproduces the final energy and bunch charge for the 400 GeV straw-man muon collider ring scenario in table 2, and table 4 provides acceleration scenarios corresponding to the two multi-TeV collider parameter sets in table 2. Apart from technical considerations, the acceleration is expected to dominate the cost of the colliders of very high energy muon colliders in particular and so cost optimization was an important consideration for the straw-man acceleration scenarios. To minimize the cost, the scenarios use configurations of recirculating linacs with "fixed field alternating gradient" (FFAG) magnet lattices that are placed in the cost-efficient layout shown in figure 1. Fast-ramping synchrotrons may also be considered (7; 6) as an alternative.

Non-decay losses of muons were neglected in the calculation of the numbers of muons per bunch, $\mathrm{N_f}$, $\mathrm{N_f^4}$ and $\mathrm{N_f^{30}}$, after each acceleration stage in the scenarios of tables 3 and 4. Decay losses were calculated (4) as follows. Muon decay losses lead to ratios of initial to final bunch populations, $\frac{N_i}{N_f}$, that are related to the recirculator tunnel lengths in units of kilometers, $L^j[km]$, the number of GeV per turn of rf acceleration, $E^j_{rf}[GeV]$, and the ratio of final to initial energies in the recirculator, $\frac{E^j_i}{E^j_f}$, through

$$\ln\left(\frac{N_f}{N_i}\right) = 0.1604 \sum_{j=1,N} \frac{L^j[km]}{E^j_{rf}[GeV]} \ln\left(\frac{E^j_i}{E^j_f}\right), \tag{1}$$

where $j = 1, N$ is the index for the j^{th} of N recirculators or linacs. Equation 1 has made the approximation of averaging the acceleration to an assumed constant gradient over the length of the recirculator as opposed to the more realistic situation where, in the case of recirculators, it will be concentrated in one or more rf linacs placed around the recirculator. This should introduce only small fractional errors in the calculated particle losses for the parameters given in tables 3 and 4.

V SUMMARY

An open invitation has been extended to participate in a six-month study of muon collider technology and physics, running from 23 October, 2000 to 22 April, 2001. The goals and structure of the study have been detailed, the collective tasks of the 5 working groups have been defined and straw-man muon collider parameter sets have been presented.

REFERENCES

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TABLE 2. Straw-man muon collider parameters. The range of parameter values for the previous parameter sets of reference (6) have been included for comparison. See text for details.

center of mass energy, E_{CoM} **description**	0.1 to 3 TeV MCC status report	400 GeV top threshold	4 TeV frontier	30 TeV many-TeV
collider physics parameters:				
luminosity, $\mathcal{L}$ [$cm^{-2}.s^{-1}$]	$(0.08 \rightarrow 700) \times 10^{32}$	3.0×10^{33}	5.0×10^{33}	3.0×10^{35}
$\int \mathcal{L}dt$ [fb^{-1}/year]	0.08→700	30	50	3000
No. of $\mu\mu \rightarrow$ ee events/det/year	650→13 000	16 000	270	290
No. of (115 GeV) SM Higgs/year	2000→800 000	14 000	55 000	5×10^6
CoM energy spread, σ_E/E [10^{-3}]	0.02→1.1	1.4	1.0	0.14
collider ring parameters:				
circumference, C [km]	0.35→6.0	1.0	8.7	45
ave. bending B field [T]	3.0→5.2	4.2	4.8	7.0
beam parameters:				
(μ^- or) μ^+/bunch, $N_0[10^{12}]$	2.0→4.0	4.0	3.5	2.3
(μ^- or) μ^+ bunch rep. rate, f_b [Hz]	15→30	15	1.0	7.5
6-dim. norm. emit., $\epsilon_{6N}[10^{-12}m^3]$	170→170	170	170	100
$\epsilon_{6N}[10^{-4}m^3.MeV/c^3]$	2.0→2.0	2.0	2.0	1.2
P.S. density, $N_0/\epsilon_{6N}[10^{22}m^{-3}]$	1.2→2.4	2.4	2.2	2.3
x,y emit. (unnorm.) [$\pi.\mu$m.mrad]	3.5→620	41	2.4	0.19
x,y normalized emit. [π.mm.mrad]	50→290	77	46	27
long. emittance [10^{-3}eV.s]	0.81 → 24	10	28	48
fract. mom. spread, δ [10^{-3}]	0.030→1.6	2.0	1.4	0.20
relativistic γ factor, E_μ/m_μ	473→14 200	1890	18 900	142 000
time to beam dump, $t_D[\gamma\tau_\mu]$	no dump	no dump	0.5	no dump
effective turns/bunch	450→780	620	450	1040
ave. current [mA]	17→30	24	0.63	12
beam power [MW]	1.0→29	3.8	2.2	83
synch. rad. critical E [MeV]	$5 \times 10^{-7} \rightarrow 8 \times 10^{-4}$	1.1×10^{-5}	0.0013	0.11
synch. rad. E loss/turn	7 eV → 0.3 MeV	0.6 keV	700 keV	450 MeV
synch. rad. power	0.1 W → 10 kW	15 W	470 W	5.2 MW
beam + synch. power [MW]	1.0→29	3.8	2.2	88
decay power into beam pipe [kW/m]	1.0→2.1	2.1	0.06	0.8
interaction point parameters:				
rms spot size, $\sigma_{x,y}$ [μm]	3.3→290	18	2.7	1.0
rms bunch length, σ_z [mm]	3.0→140	7.5	3.0	4.8
$\beta^*_{x,y}$ [mm]	3.0→140	7.5	3.0	4.8
rms ang. divergence, σ_θ [mrad]	1.1→2.1	2.3	0.90	0.20
beam-beam tune disruption, $\Delta\nu$	0.015→0.051	0.056	0.083	0.092
pinch enhancement factor, H_B	1.00→1.01	1.02	1.08	1.09
beamstrahlung frac. E loss/collision	negligible	negligible	6×10^{-9}	9×10^{-8}
final focus lattice parameters:				
max. poletip field of quads., $B_{5\sigma}$ [T]	6→12	10	12	15
max. full aper. of quad., $A_{\pm 5\sigma}$[cm]	14→24	18	18	18
quad. gradient, $2B_{5\sigma}/A_{\pm 5\sigma}$[T/m]	50→90	110	130	160
approx. β_{max}[km]	1.5→150	8	140	1800
ff demag., $M \equiv \sqrt{\beta_{max}/\beta^*}$	220→7100	100	7000	19 000
chrom. quality factor, $Q \equiv M \cdot \delta$	0.007→11	0.003	10	4
neutrino radiation parameters:				
collider reference depth, D[m]	10→300	20	300	100
ave. rad. dose in plane [mSv/yr]	2×10^{-5}→0.02	7×10^{-4}	9×10^{-4}	6
str. sec. len. for 10x ave. rad. [m]	1.3→2.2	1.6	1.1	1.9
ν beam distance to surface [km]	11→62	16	62	36
ν beam radius at surface [m]	4.4→24	8.4	3.3	0.25

TABLE 3. Straw-man acceleration parameter sets corresponding to the 400 GeV muon collider ring scenario in table 2. The parameter N_f is the number of muons per bunch at the exit of each FFAG See text for detailed explanations.

i	type	E_i [GeV]	E_f [GeV]	$\frac{E_f}{E_i}$	# turns	E_{rf} [GeV]	rf grad. [MV/m]	L_{linacs} [km]	B_{ave} [T]	L_{arcs} [km]	circum. [km]	$f_{survive}$	N_f [10^{12}]
0	cooling		0.19										5.15
1	linacs	0.19	3	16.1	–	2.81	5.0	0.56	–	–	0.56	0.915	4.71
2	recirc.	3	12	4.00	4	2.25	9.0	0.25	1.3	0.200	0.45	0.957	4.51
3	recirc.	12	50	4.17	5	7.6	15.2	0.50	2.1	0.500	1.00	0.970	4.37
4	FFAG	50	125	2.50	30	2.5	20	0.125	3.0	0.875	1.00	0.943	4.12
5	FFAG	125	200	1.60	30	2.5	20	0.125	4.8	0.875	1.00	0.970	4.00

TABLE 4. Straw-man acceleration parameter sets for high energy muon colliders at 4 TeV and 30 TeV. The acceleration scenarios for these two collider energies have been included in the same table because most of the parameters in the table are the same up to the 2 TeV beam energy of the lower energy scenario. However, this correspondence is not expected to extend to more detailed scenarios. The parameter sets N_f^4 and N_f^{30} are the numbers of muons per bunch at the exit of each FFAG corresponding to the 4 TeV and 30 TeV muon collider ring scenarios in table 2, respectively. See text for detailed explanations.

i	type	E_i [GeV]	E_f [GeV]	$\frac{E_f}{E_i}$	# turns	E_{rf} [GeV]	rf grad. [MV/m]	L_{linacs} [km]	B_{ave} [T]	L_{arcs} [km]	circum. [km]	$f_{survive}$	N_f^4 [10^{12}]	N_f^{30} [10^{12}]
0	cooling		0.19										5.06	3.85
1	linacs	0.19	3	16.1	–	2.81	5.0	0.56	–	–	0.56	0.915	4.63	3.52
2	recirc.	3	12	4.00	4	2.25	9.0	0.25	1.26	0.200	0.45	0.957	4.43	3.37
3	recirc.	12	50	4.17	5	7.6	15.2	0.50	2.09	0.500	1.0	0.970	4.30	3.27
4	FFAG	50	125	2.50	3	25	20	1.25	.351	7.45	8.7	0.950	4.09	3.11
5	FFAG	125	250	2.00	5	25	20	1.25	.703	7.45	8.7	0.962	3.93	2.99
6	FFAG	250	500	2.00	10	25	20	1.25	1.41	7.45	8.7	0.962	3.78	2.88
7	FFAG	500	1000	2.00	20	25	20	1.25	2.81	7.45	8.7	0.962	3.64	2.77
8	FFAG	1000	1500	1.50	20	25	20	1.25	4.22	7.45	8.7	0.984	3.56	2.70
9	FFAG	1500	2000	1.33	20	25	20	1.25	5.62	7.45	8.7	0.984	3.50	2.66
10	FFAG	2000	5000	2.50	30	100	25	4.00	2.55	41	45	0.936		2.49
11	FFAG	5000	10 000	2.00	50	100	25	4.00	5.11	41	45	0.951		2.37
12	FFAG	10 000	15 000	1.50	50	100	25	4.00	7.66	41	45	0.971		2.30